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JAN 78 P J HOGAN, V HOPKINS F33615-75-C-5116

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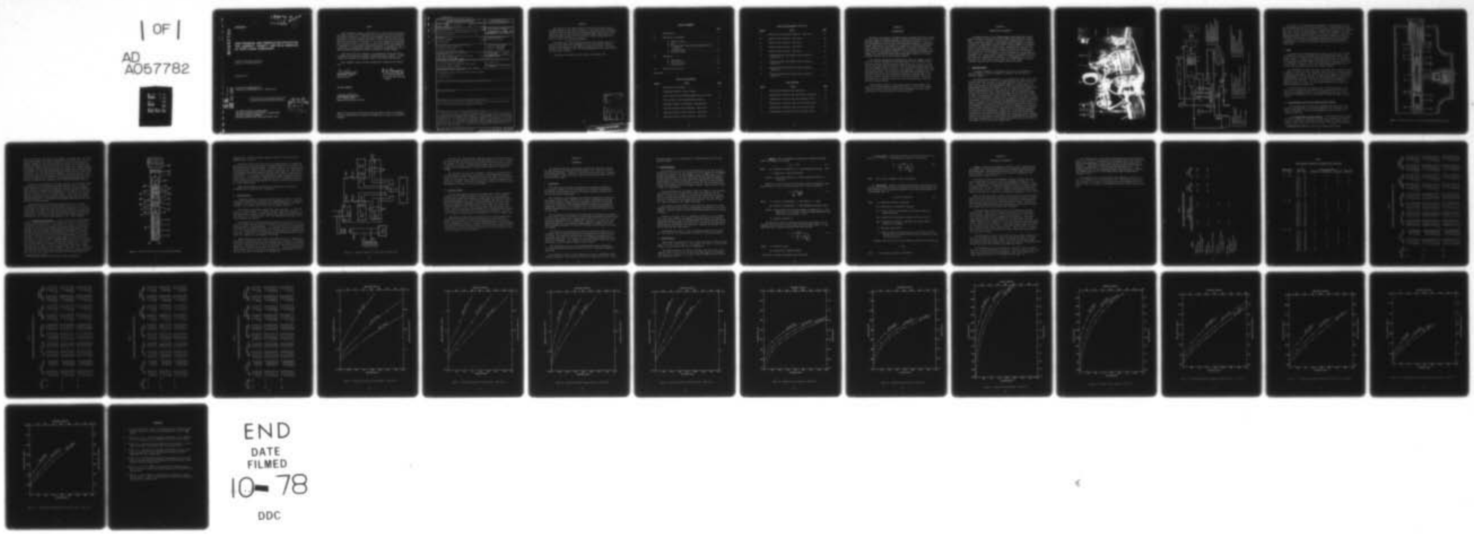

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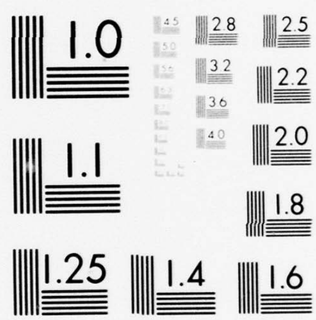

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HIGH PRESSURE AND TEMPERATURE EFFECTS ON THE VISCOSITY, DENSITY, AND BULK MODULUS OF FOUR LIQUID LUBRICANTS

MIDWEST RESEARCH INSTITUTE
KANSAS CITY, MISSOURI 64110

JANUARY 1978

Technical Report AFML-TR-78-5
Final Report for Period January 1977 - December 1977

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Project Monitor

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FOR THE DIRECTOR

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Absolute viscosity, kinematic viscosity, density, and secant bulk modulus values determined for four lubricating fluids are presented. The determinations were made with a falling weight viscometer at temperatures of 38°C (100°F) 99°C (210°F), and 149°C (300°F) and at pressures ranging from atmospheric to 1103 MPa (160,000 psi). Plots of absolute viscosity, density, and bulk modulus are given, and all results are discussed. The equipment used to make the determinations is described, and the procedures followed to collect data and reduce to fluid property values are outlined. The fluids were designated MLO 75-122, MLO 76-121, MLO 77-39, and MLO 77-46.

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FOREWORD

The purpose of this work has been to determine viscosity, density, and bulk modulus of four liquid lubricants. The work has been conducted at Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110, for the Air Force Materials Laboratory (MBT), under Contract No. F33615-75-C-5116 (January 2, 1975 to April 1, 1978), Project No. 7343, Task No. 434303, MRI Project No. 4023-L.

Mr. Frederick C. Brooks of the Lubricants and Tribology Branch, Air Force Materials Laboratory (AFML/MBT), has been the project engineer. Messrs. Patrick Hogan and Vern Hopkins prepared this report. Mr. Hogan conducted the laboratory work. Mr. Karl Mecklenburg is the project leader for the overall program.

The report was submitted by the authors in December 1977.

TABLE OF CONTENTS

List of Illustrations

List of Illustrations (Continued)

List of Tables

SECTION I

INTRODUCTION

Viscosity, the constant of proportionality relating fluid shear stress to shear strain for Newtonian liquids, is generally considered to be the most important property of liquid lubricants and hydraulic fluids. Because of the relationship between viscosity and fluid-film thickness in elastohydrodynamic lubrication, this property is significant in determining friction loss, mechanical efficiency, heat generation, fluid flow, load-carrying capacity, and wear of machine components such as bearings and gears. Viscosity will vary appreciably because of the large pressure and temperature changes that occur within liquid films which move in and out of the concentrated contact zone of such machine elements.

This work was undertaken to determine the effect of changes in pressures to 1103 MPa (160,000 psi) and temperatures to 149°C (300°F) on the viscosity, density, and bulk modulus characteristics of four liquid lubricants. These four fluids consisted of MLO-75-122 (MIL-L-83282A), MLO-76-121 (MIL-L-5606C), MLO-77-39 (Freon E 6.5), and MLO-77-46 (Halocarbon AO-8). Data on these fluids were taken with a falling-weight viscometer and a compressibility fixture. Fall time and compressibility measurements were generally made at 138 MPa (20,000 psi) intervals of pressure and at temperatures of 38°C (100°F), 99°C (210°F), and 149°C (300°F). These data were then used to determine values for absolute and kinematic viscosity, density, and bulk modulus.

The following sections of this report describe the equipment used (II); outline the procedures followed to collect the data (III); present viscosity, density, and bulk modulus values determined for both fluids, and discuss the characteristics of the fluids (IV).

SECTION II

DESCRIPTION OF EQUIPMENT

An advanced version of the high-pressure, high-temperature falling weight viscometer, described in the 1953 ASME Pressure Viscosity Report (Ref. 1), is used to measure the viscosity and compressibility of lubricating fluids (see Figure 1). The falling-weight viscometer is designed to operate at temperatures from 0°C (32°F) to 204°C (400°F) and pressures from 0 to 1,724 MPa (0 to 250,000 psig). Compressibility data and fall time data are measured and used to calculate absolute and kinematic viscosity, density, and bulk modulus of the fluids tested. The viscometer unit consists of: (a) a hydraulic system to provide the high-pressure environment; (b) a liquid bath to provide the thermal environment; (c) falling weight and compressibility fixtures; (d) instrumentation to collect data; and (e) a roll-over system to cause the falling weight to fall alternately from one end of the viscometer tube to the other.

A. Hydraulic System

A schematic diagram of the hydraulic circuit of the viscometer is shown in Figure 2. Items 8 through 26 of Figure 2 are all part of a rotating assembly.

The high-pressure environment in the high-pressure chamber (21), which contains either the viscosity or the compressibility fixture, is built in three stages. The air-operated hydraulic pump (8) is first used to increase the pressure in the high-pressure chamber, transition tube, and high-pressure cylinder (18) directly to 48 to 55 MPa (7,000 to 8,000 psig). The 10:1 intensifier (16) is then actuated to increase the pressure to about 345 MPa (50,000 psig). Items (18), (21), and the connecting tubing (transition tube) now contain all the hydraulic fluid that will be added to them. The low-pressure cylinder (14), which has an area about 49 times that of the high-pressure cylinder (18), is actuated for the final increase in pressure. As the piston (19) for the high-pressure cylinder advances because of loading by the low-pressure cylinder piston, the port used to introduce hydraulic fluid (into 18) below 345 MPa (50,000 psig) is vented to the atmosphere, and the fluid in (18) and (21) is trapped. Very high pressures can now be developed in (18) and (21), with only moderate increases of pressure in the low-pressure cylinder (14). On decreasing pressure, the piston for the high-pressure cylinder will retract the low-pressure cylinder most of the way as the hydraulic and test fluids expand. Complete return of the low-pressure cylinder piston is accomplished by pressurizing the backup cylinder (13). This cylinder mechanically forces the return of the piston in the low-pressure cylinder (14).

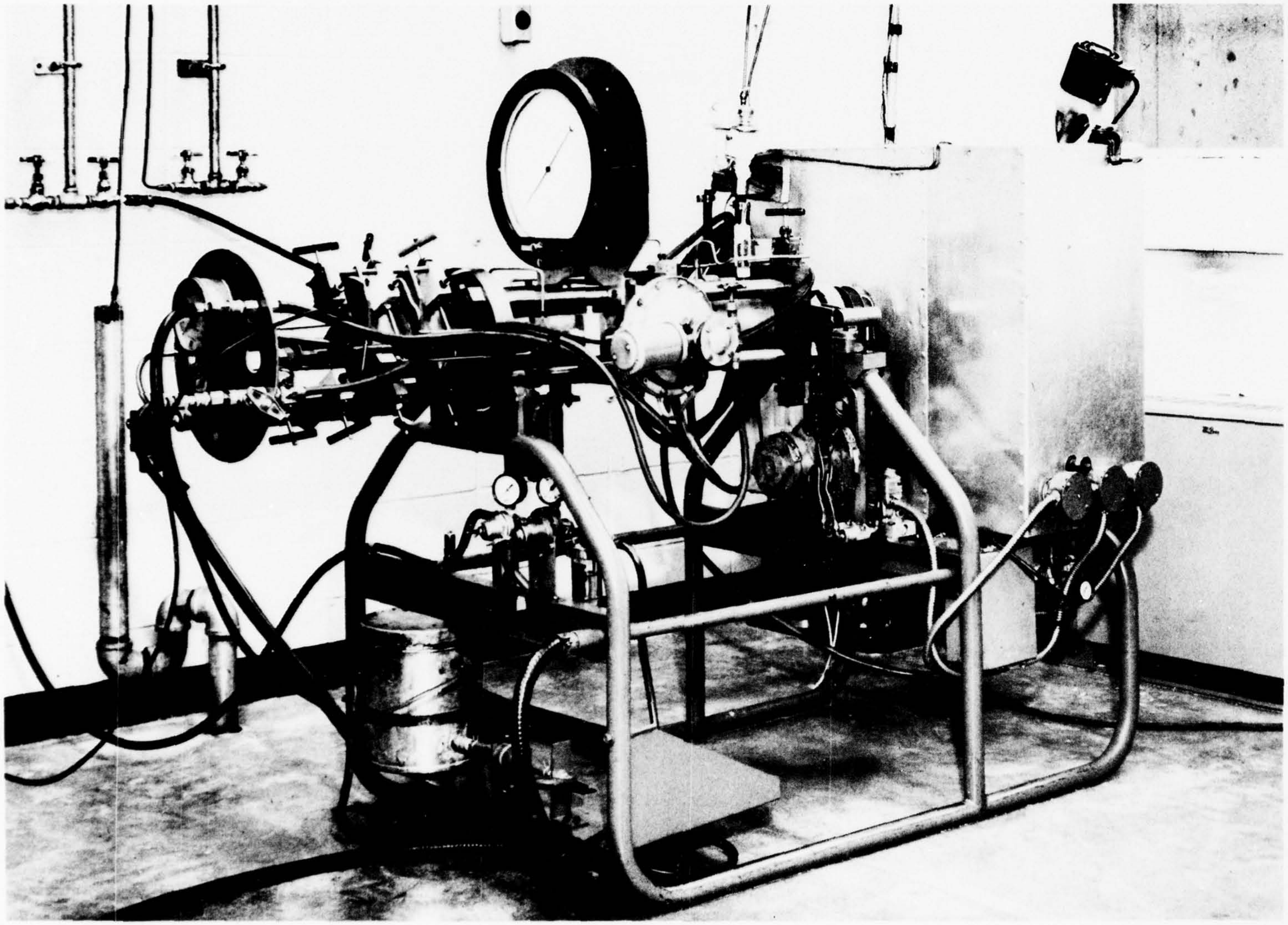
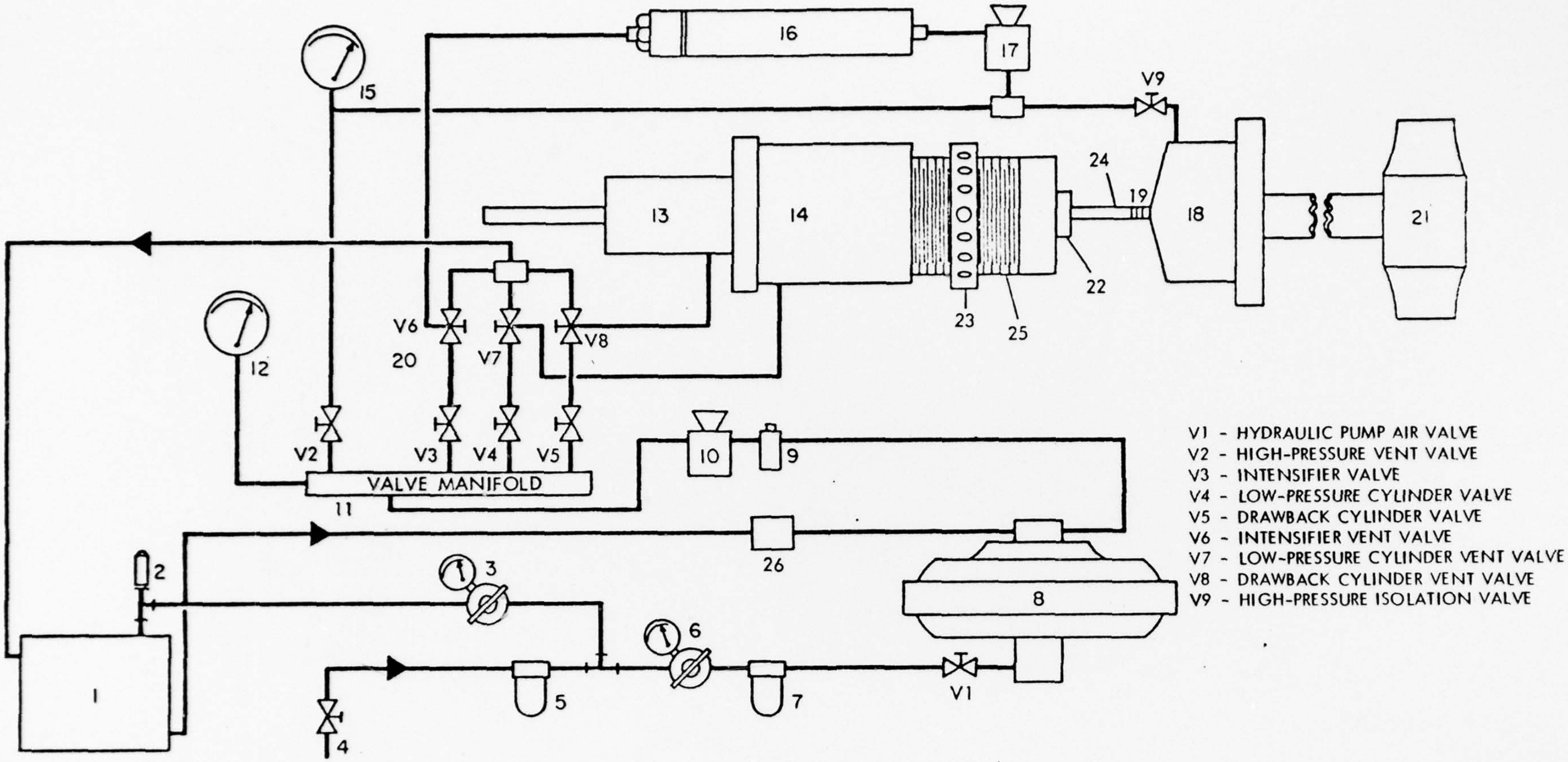


Figure 1 - High Pressure Viscometer



V1 - HYDRAULIC PUMP AIR VALVE
V2 - HIGH-PRESSURE VENT VALVE
V3 - INTENSIFIER VALVE
V4 - LOW-PRESSURE CYLINDER VALVE
V5 - DRAWBACK CYLINDER VALVE
V6 - INTENSIFIER VENT VALVE
V7 - LOW-PRESSURE CYLINDER VENT VALVE
V8 - DRAWBACK CYLINDER VENT VALVE
V9 - HIGH-PRESSURE ISOLATION VALVE

1 - RESERVOIR
2 - RESERVOIR RELIEF VALVE
3 - RESERVOIR REGULATOR
4 - UTILITY AIR
5 - WATER TRAP
6 - PUMP - REGULATOR
7 - OILER
8 - PUMP
9 - BLOW OUT SNUBBER
10 - 69 MPa (10,000 PSIG) RUPTURE DISC
11 - VALVE MANIFOLD
12 - PUMP DISCHARGE PRESSURE
13 - DRAWBACK CYLINDER
14 - LOW-PRESSURE CYLINDER
15 - HIGH-PRES. 345 MPa (50,000 PSIG) HEISE GAGE
16 - INTENSIFIER
17 - 379 MPa (55,000 PSIG) RUPTURE DISC
18 - HIGH-PRES. CYLINDER & TRANSITION TUBE
19 - HIGH-PRESSURE CYLINDER PISTON HEAD
20 - SYSTEM CONTROL VALVES
21 - HIGH-PRESSURE CHAMBER
22 - BACKING PIECE
23 - LOCKING COLLAR
24 - PISTON-HIGH PRESSURE CYLINDER
25 - PISTON-LOW PRESSURE CYLINDER
26 - FLUID FILTER

Figure 2 - Viscometer Hydraulic Control System

The level of the high-pressure environment in the high-pressure cylinder and chamber (18 and 21) is indicated either by a Bourdon-tube pressure gage (below 345 MPa (50,000 psi)), or by the change in resistance of a manganin wire coil located in the high-pressure cylinder. The manganin wire transducer has a linear resistance change as a function of pressure. This linear pressure-resistance characteristic is useful from atmospheric pressure to 2,930 MPa (425,000 psi). The calibration constant of the coil is checked at pressures up to 689 MPa (100,000 psi) with a precision Bourdon-tube pressure gage. Pressures above 689 MPa (100,000 psi) are measured by extrapolation.

B. Bath

A stirred constant-temperature bath, shown at the right end of Figure 1, provides the thermal environment for the high-pressure chamber. This chamber (Item 21 in Figure 2) contains either the viscosity or compressibility fixture. A phenyl-methyl silicone (QF-258) is used as a bath fluid at temperatures above 10°C (50°F). The bath vessel is equipped with a coil for tap water, an evaporator coil for a small refrigeration unit, three 1,500 w electric heaters, and one 500 w electric heater.

At 20°C (68°F) and above, one or more of three 1,500 w heaters are used to supply the bulk of the heat required. These heaters are controlled by a solid-state power supply. The output of this power supply is controlled by a thermocouple in the bath liquid. In order to have positive control near room temperature, both the heaters and the refrigeration system may be operated at the same time. The coil for tap water is used primarily to hasten cooling of the bath. The bath liquid temperature is measured by ASTM extended-range thermometers.

An electric-motor-driven pump and 0.114 m^3 (30-gal.) drum are connected to the temperature controlled bath to transfer and hold the bath fluid while changing specimens. This arrangement prevents the loss of bath fluid, and minimizes the time required to change specimens or replace a seal.

C. Falling-Weight Viscosity and Compressibility Fixtures

The falling-weight viscosity and compressibility fixtures are the heart of the high-pressure viscometer apparatus. The remainder of the setup is designed to control the environment for these fixtures or to take data from them.

1. Falling-weight viscosity fixture: A cross section of the fixture is shown in Figure 3.* This device consists of a cylinder (1) in which slides a closely-fitted cylindrical falling weight (2). There is an insulated contact (3a) at each end of the tube. The contacts are locked in

* Reprinted from ASME Pressure-Viscosity Report and modified.

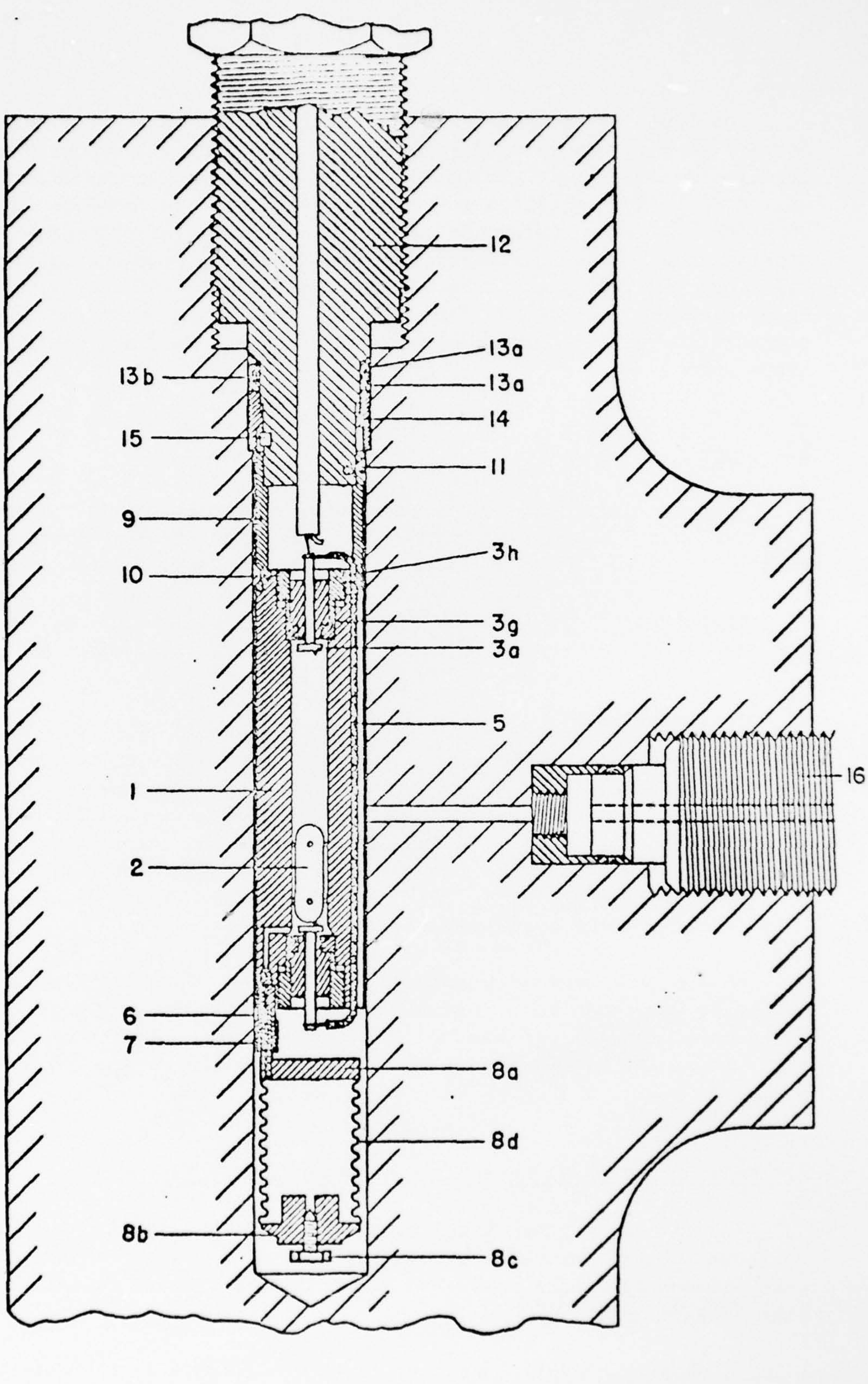


Figure 3 - Cross Section of the Falling Weight Fixture in Place

place by nuts (3h), and sealed by lead washers or O-rings (3g). The flexible bellows assembly (8), which is connected to the lower end of the viscometer cylinder by a tube (6) and union (7), serves as a reservoir to keep the viscometer tube filled with the test fluid, and to transmit the hydrostatic pressure outside the fixture to the test fluid without appreciable change. The insulted contacts (3a) are connected by a wire (5) which is attached to a lead extending through the terminal plug (12) which, with seals (13), closes the high-pressure chamber. The entire fixture is surrounded by the pressure-transmitting fluid introduced through the extension (16) of the high-pressure chamber. The pressure-transmitting fluid is a mixture of normal hexane containing 5% (by volume) SAE 20-20W motor oil.

Viscosity is proportional to the time required for the falling weight to descend vertically through the cylinder under the force of gravity. Repeat readings are taken by rotating the viscometer one-half revolution. This rotation is accomplished by turning the entire hydraulic system (except the reservoir) about its horizontal axis. The time of fall is indicated by a counter accurate to within 1/60 sec. The counter is started when the weight breaks contact with the upper cylinder and plug, and is stopped when contact is established by the weight touching both the cylinder and the bottom end plug.

The electrical leads through the terminal plug are in a swaged stainless-steel sheath which is silver-brazed to an air-quenched tool-steel plug. Six conductors, four iron and two constantan, are contained in the 0.63 cm (1/4-in.) OD sheath and are insulated with very dense magnesium oxide. To reduce the chance of leakage of hexane, the MgO is impregnated with polyimide resin at roughly 345 MPa (50,000 psig) and then cured (about 1 hr at 107°C (225°F) and then 1 hr at 260°C (500°F)).

2. Compressibility fixture: A cross section of the compressibility fixture is shown in Figure 4.* The liquid test sample is sealed into the bellows (1) under vacuum. The bellows are welded to the end pieces (2) and (3), and contain the guides (4) and (5), which keep the bellows straight and assure a linear length/volume-change relationship for the bellows. This relationship was experimentally determined. The guides are held in place and the bellows ends sealed by silver solder. After filling the bellows with test fluid, the filling opening is sealed by a screw (8). The bellows assembly is then clamped to the sleeve (12) by the nut (13). A short length of polished high-resistance 0.45 mm (0.0179 in.) diameter Nirex wire (11) is attached to the upper end of the bellows and, as the pressure is increased, the bellows become shorter, causing the Nirex wire to slide over the insulated contact (15) which is fixed in the block (14) which in turn is clamped to the sleeve (12). Leads from the slide wire (11) and the insulated contact (15) are soldered to terminals (23) which are connected to the leads (30) extending through the

* Reprinted from ASME Pressure-Viscosity Report and modified.

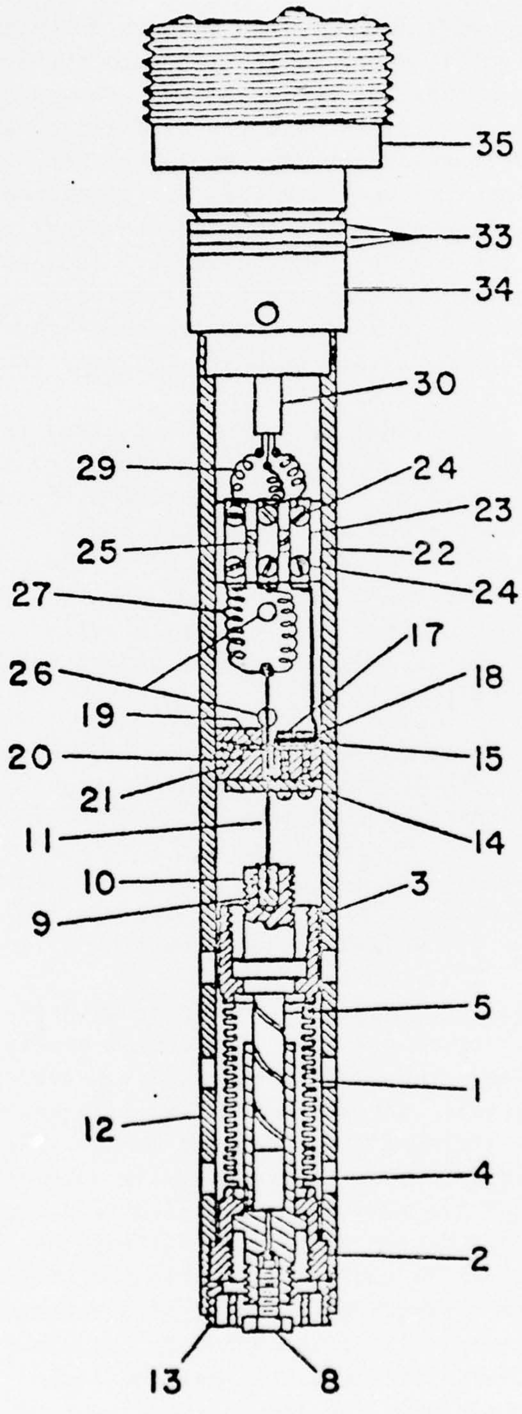


Figure 4 - Cross Section of the Compressibility Fixture

terminal plug. Identical terminal plugs are used for the viscosity and compressibility fixtures.

The motion of the slide wire over the insulated contact is measured by determining the voltage drop between the contact soldered to the end of the Nirex wire and the insulated contact. Separate leads are used to measure the voltage drop and to supply the bias voltage to the Nirex wire. The relationship between voltage drop change and bellows-length change is established experimentally at the various test temperatures, using a micrometer head and a small oven. The relationship between bellows-length change and bellows-volume change is experimentally determined by use of a micrometer head with a precision capillary tube that measures the change in bellows volume caused by a known length change.

Additional information concerning the development of the present viscometer will be found in Refs. 2 through 5.

D. Instrumentation

A schematic diagram of the instrumentation used to measure: (a) pressures with a manganin coil transducer; (b) compressibility with a slide wire transducer; and (c) the time required for the falling weight to fall from one end of the viscometer tube to the other is shown in Figure 5.

All electrical measurements except fall times were made on a Leeds and Northrup K-3 Potentiometer. To measure voltages, leads were connected to the potentiometer through Leeds and Northrup instrumentation switches having less than 0.1 μv of thermal noise. Fall-time measurements were made with a Hewlett-Packard 5325 Counter.

The manganin-coil pressure-measuring system uses a four-wire system to permit the leads carrying current to the coil to be separated from the voltage measuring leads to the potentiometer. A 100-ohm precision resistor connected in series with the manganin coil was used to monitor the current through the coil. This current can be monitored with a potentiometer or a separate microvoltmeter. Calibration of the microvoltmeter was checked before each test to assure the stability of the manganin coil current.

Midway through testing the second fluid (MLO 76-121), the manganin-coil developed an intermittent short circuit between coils and had to be replaced. The new coil was heat treated and then pressure aged to minimize drift during operation. Calibration of the coils was checked at least once for each fluid. Sensitivity to pressure was the same for each coil. It was established that results from either coil allowed the pressure to be reproducible to ± 0.35 MPa (± 50 psi) from 0 to 689 MPa (0 to 100,000 psi).

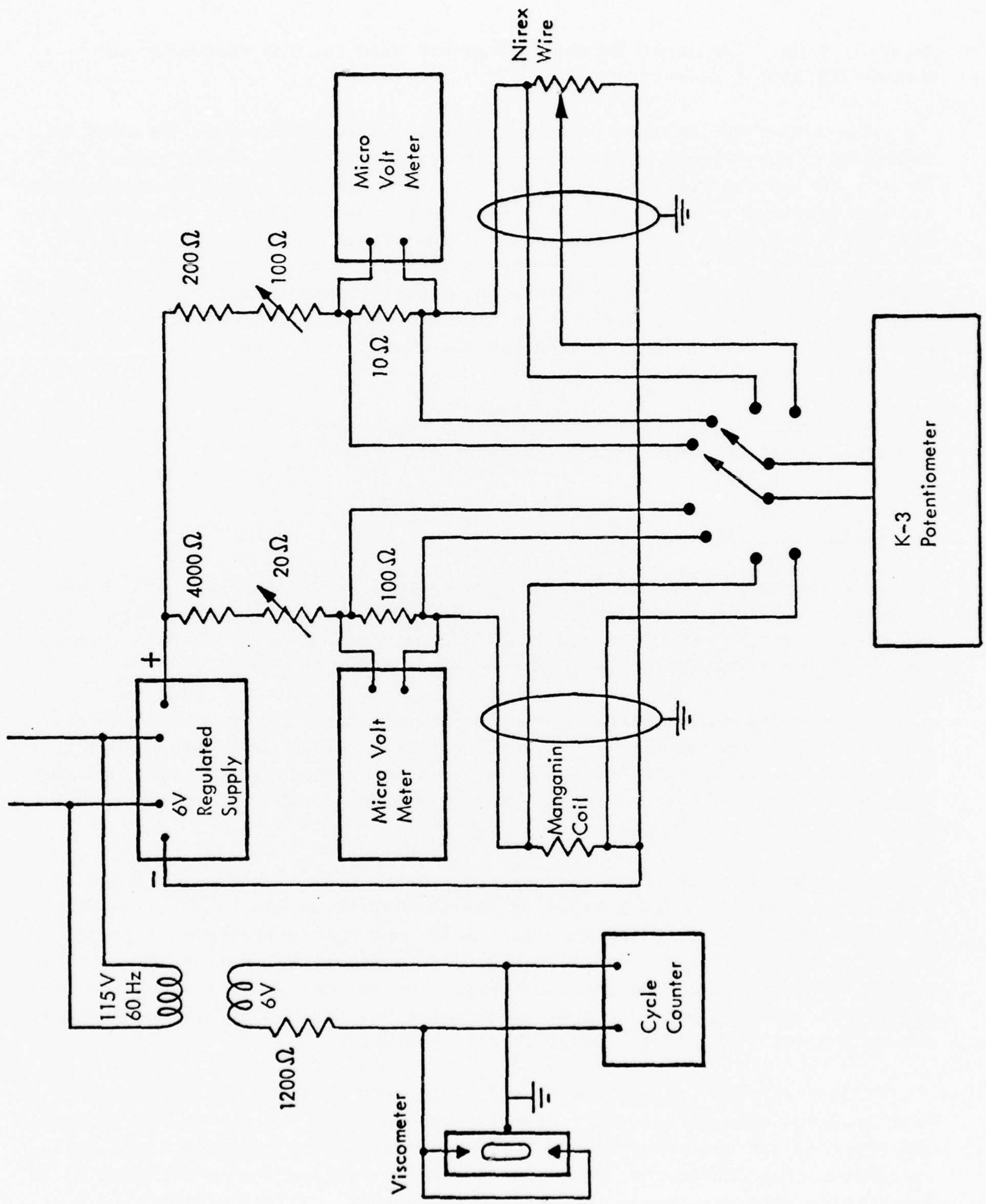


Figure 5 - Schematic Diagram of Viscometer Instrumentation

The Nirex wire compressibility measuring system is a four-wire system; one pair supplies the bias current, while the second pair is used to measure the voltage. The voltage drop across a 10-ohm precision resistor is used to monitor the current. A second microvoltmeter can be used to monitor the current while the potentiometer is being used to measure the Nirex wire voltage.

The laboratory in which the viscometer is located is equipped with an air-conditioning system capable of holding the room temperature constant within $\pm$ 0.25°C ($\pm$ 0.5°F). Temperatures varied less than $\pm$ 0.1°C ($\pm$ 0.2°F) inside the instrument console where the critical electrical measuring components are located. This control of laboratory temperature permits accurate measurements to be made in an efficient manner.

E. Roll-Over System

This falling-weight viscometer is equipped with a remotely operated rotating device to provide uniform rates of rotation of the viscometer fixture, and to permit the operator to remain away from dangerous areas during high-pressure runs. The system is pneumatic and uses 0.41 to 0.62 MPa (60 to 90 psig) air pressure. A partial-revolution air motor turns the entire hydraulic system 180 degrees in less than 1 sec, and thereby causes the weight to fall through the viscometer tube filled with test fluid. The air motor, which is connected to the rotating assembly through a timing belt, is supplied with air through one of two ports. The direction of rotation is controlled by the position of a four-way solenoid valve.

Cam-operated valves sense the position of the rotating assembly and adjust the air flow rate to permit deceleration of the assembly to a smooth, but firm, halt on one of the two adjustable stops. Adjustments can be independently made in: (a) the angular position of the test chamber, the cams, and the stop arm with respect to the transition (hydraulic fluid supply) tube; (b) the actuating air pressure; (c) the stop positions; and (d) the settings of the air snubbers.

SECTION III

PROCEDURES

The procedures followed to determine high-pressure viscosity, density, and bulk modulus values consisted of three steps. The first step involves calibrating transducers. During the second step the overall unit is operated to collect data. In the third step, data are reduced to viscosity, density, and bulk modulus values.

A. Calibration

The high-pressure viscometer incorporates two measuring transducers which require regular checks of calibration and occasional recalibration. In addition, the viscometer tube has two pointed electrical contacts which must be occasionally resharpened.

The calibration of the manganin-coil pressure transducer was checked at least once for each fluid. While the coil had to be replaced once during the testing, both the original and the replacement coils had the same sensitivity to pressure so this change presented no problems to experimental consistency. Resistance of the manganin wire coil was calibrated against a 689 MPa (100,000 psi) Heise bourdon-tube gauge, which was certified to 0.1% of full scale.

The calibration of the Nirex wire compressibility transducer was checked at least once for each fluid tested. The resistance/displacement characteristic of the wire was measured with a potentiometer and a 0 to 2.54 cm (0 to 1 in.) micrometer graduated in 2.5 μm (0.0001 in.) increments. The Nirex wire was replaced during one of the specimen changes because of damage to the wire. This replacement resulted in two sets of reference currents being used during the testing.

Fall length must be measured each time the electrical contacts in the viscometer tube are sharpened because the distance which the weight can fall is altered. The length is measured with an adjustable plug gage, which is in turn measured with a 0 to 5 cm (0 to 2 in.) micrometer graduated in 25 μm (0.001 in.) increments. The length of the falling weight is subtracted from the length of the plug gage to obtain the fall length.

Bath temperatures are set by using ASTM extended range thermometers, and are held constant within $\pm$ 0.05°C ($\pm$ 0.1°F) by a three-mode temperature controller.

The vertical position of the viscometer tube axis is checked after each change of specimens. The position is set within 1 degree of vertical, using a precision level ($\pm$ 30 min) positioned on a machined surface of the high-pressure chamber.

B. Data Collection

Data required for the viscosity determination are the fall time and the density of the fluid in the viscometer at each temperature and pressure of the test schedule. The test schedule called for temperatures of 38°C (100°F), 99°C (210°F), and 149°C (300°F) and pressures from atmospheric to 965 MPa (140,000 psig). At each temperature, the pressure was increased in increments of 138 MPa (20,000 psi) to a maximum of 1,103 MPa (160,000 psig) or until the fall time exceeded 780 sec. In some cases smaller increments of pressures were used to permit taking at least four data points at each test temperature.

The time required for the weight to fall the length of the viscometer tube filled with the test fluid was recorded to the nearest 1/60 of a second. At least five readings of fall time were taken when the viscometer was rolled to the left and five when it was rolled to the right, except at the longest fall time (greater than 10 min). Only two or three fall times were taken at the longest fall times.

The volume of a known weight of test fluid was measured in the compressibility fixture at each of the temperatures and pressures of the test schedule. Pressure limits were those established during the fall time measurements.

Density of the test fluid, at atmospheric pressure for each temperature of the test schedule, was measured concurrently with the compressibility measurements, using two different makes of specific-gravity bottles immersed in the temperature-controlled bath. The simultaneous density and compressibility measurements are expected to eliminate any possible error due to different bath temperatures.

Measurements were made in order of increasing temperature and pressure, and rechecks of selected points were made on decreasing pressure.

C. Data Reduction

Three computer programs are used to reduce the data to values of density, bulk modulus, and viscosity. The programs are helpful in reducing the number of errors and the cost of the computations.

The computer programs are written to accept some of the data in the English system of units. Once the data have been reduced, the programs make necessary conversions to S.I. units and then output the data in both S.I. and English units.

1. Density: Data at atmospheric pressure are smoothed by fitting them to an equation of the form

$$\rho_O = a + bT \qquad \text{EQ. 1}$$

where ρ_O = density at temperature T and atmospheric pressure, g/ml

T = temperature, degrees Fahrenheit

a and b = constants determined by a linear regression curve fit procedure.

Densities at test pressures are calculated from the atmospheric pressure density data and the compressibility data using the equation

$$\rho = \frac{1}{\frac{1}{\rho_O} - \frac{(V_O - V)}{W}} \qquad \text{EQ. 2}$$

where ρ = density at temperature T and pressure P, g/ml

ρ_O = density at temperature T and atmospheric pressure, g/ml

$(V_O - V)$ = volume change of test fluid sample at temperature T, and subjected to an increase in pressure from atmospheric pressure to the test pressure P, ml

W = weight of sample, g.

An equation is fitted to the density-pressure-temperature data to smooth it in a way that all data points will have equal weight. It has been found that a suitable equation will have the form

$$\rho = \frac{\rho_O \gamma}{\gamma - \ln\left(1 + \frac{P}{\alpha + \frac{\beta}{T_R}}\right)} \qquad \text{EQ. 3}$$

where P = pressure, psig

T_R = temperature, degrees Rankine

α, β and γ = constants dependent upon the fluid.

2. <u>Bulk modulus</u>: Bulk modulus values are calculated from the constants α, β and γ determined above using the relationship

$$\bar{B}_T = \frac{\gamma P}{\ln\left(1 + \dfrac{P}{\alpha + \dfrac{\beta}{T_R}}\right)} \qquad \text{EQ. 4}$$

where $\bar{B}_T$ is the isothermal secant bulk modulus.

3. <u>Viscosities</u>: Absolute viscosity and kinematic viscosity are calculated from the fall time data, the density data and the form factors for the viscometer, using the equation presented in the 1953 ASME Pressure Viscosity Report (Ref. 1):

$$\mu = (C_f\, C'\, C_b\, C_d)\, T/L \qquad \text{EQ. 5}$$

where μ = absolute viscosity, centipoise

C_f = form factor or calibration constant

C' = factor related to the geometry of falling weight and viscometer tube

C_b = correction for bouyancy of sinker in the test fluid

C_d = correction for thermal expansion and compressibility effects on viscometer

L = distance sinker falls

T = time for sinker to travel distance L at constant velocity; measured fall time corrected for time to accelerate sinker to final velocity.

Kinematic viscosity is the ratio of absolute viscosity to the density.

$$\nu = \frac{\mu}{\rho} \qquad \text{EQ. 6}$$

where ν = kinematic viscosity, centistokes.

SECTION IV

RESULTS AND DISCUSSION

Changes in absolute and kinematic viscosity, as well as density and bulk modulus, have been determined for four lubricants at high pressures and temperatures. Representative properties of these sample fluids are given in Table 1. The test conditions at which the experimental data were taken are listed in Table 2.

The values of absolute and kinematic viscosity, density, and bulk modulus determined for the four fluids are presented in Tables 3, 4, 5, and 6. These same fluid properties are also plotted as functions of pressure and temperatures. The absolute viscosity of the four fluids is shown in Figures 6, 7, 8, and 9. The fluid densities related to pressure are given in Figures 10, 11, 12, and 13. Finally, the isothermal-secant bulk modulus as a function of pressure is presented in Figures 14, 15, 16, and 17.

MLO 77-39 was the highest viscosity liquid of the four fluids tested. MLO 77-46 was the second most viscous fluid, being only slightly less than MLO 77-39. MLO 76-121 was the third most viscous fluid, while MLO 75-122 was the lowest viscosity liquid of the four fluids tested. In addition, MLO 75-122 viscosity properties were significantly less sensitive to pressure change than those of the other three lubricants.

The density data showed that the four fluids formed two distinct density ranges. MLO 75-122 was similar to MLO 76-121, with both fluids having densities ranging from 750 to 1,010 Kg/m^3 (0.750 to 1.010 g/ml) over a pressure range of 0 to 1,103 MPa (0 to 160,000 psi). The second range consisted of MLO 77-39 and MLO 77-46 with each having densities ranging from 1,550 to 2,125 Kg/m^3 (1.550 to 2.125 g/ml) over a pressure range of 0 to 758 MPa (0 to 110,000 psi). In the lower density range, MLO 76-121 was the denser of the two fluids. In the higher density range, MLO 77-39 had a slightly higher density than MLO 77-46. These fluids in the higher range were also much more sensitive to pressure change than were those in the lower density range.

The bulk modulus of MLO 75-122 and MLO 76-121 are nearly identical at the three temperatures tested. These two lubricants display the highest bulk modulus of the four fluids tested. MLO 77-46 has the next highest bulk modulus, being only slightly less than that of MLO 75-122 and MLO 76-121. Of the four fluids, MLO 77-39 has the lowest bulk modulus.

The experimental procedure followed for these four fluids is nearly identical to those methods used in the past. For this reason, results from these four fluids are directly comparable to those fluids reported on in reports AFML-TR-74-195 (Ref. 6) and AFML-TR-76-240 (Ref. 7).

The probable error of the density and bulk modulus values reported in Tables 3, 4, 5, and 6 is estimated to be no greater than ± 0.3%. Of the 71 density determinations, 70 are within ± 0.3% of the value calculated by Equation 3. The computer programs for reducing the density data also calculate the standard error of the estimate for Equations 1 and 3. The standard error for all the atmospheric density data combined is 0.36% and the standard error for all of the high-pressure density measurements combined is 0.16%.

The probable error of the viscosity values reported in Tables 3, 4, 5, and 6 is estimated to be no greater than ± 5%. This estimate is based on the variation of fall times at each data point and the repeatability of the fall times. At present, no procedures are used to smooth the viscosity data.

TABLE 1

FLUID SAMPLE REPRESENTATIVE PROPERTIES

Sample	Viscosity ($\mu m^2/s$ (CST)) At 37.8°C (100°F)	Viscosity ($\mu m^2/s$ (CST)) At 98.9°C (210°F)	Flash Point °C	Flash Point (°F)	Fire Point °C	Fire Point (°F)
MLO-75-122 MIL-L-83282A (Brayco Micronic 882) Bray Oil Company	15.7	3.54	218	425	254	490
MLO-76-121 MIL-L-5606C Lot 44 Roy Lubricants Company	14.1	5.2	104	220	110	230
MLO-77-39 Freon E 6.5 E. I. du Pont de Nemours and Company, Inc.	5.18	1.36	-	-	-	-
MLO-77-46 Halocarbon AO-8 Batch 02877 Halocarbon Products Corporation	7.41	2.13	-	-	-	-

TABLE 2

HIGH-PRESSURE VISCOSITY AND DENSITY TEST CONDITIONS

Temperature		Pressure		Liquid Lubricants			
°C	(°F)	MPa	(psi)	MLO 75-122	MLO 76-121	MLO 77-39	MLO 77-46
38	100	0	0	X	X	X	X
		68.9	10			X	X
		137.9	20	X	X	X	X
		206.8	30		X	X	X
		241.3	35			X	
		275.8	40	X	X		X
		344.7	50	X	X		
		379.2	55		X		
		413.7	60	X			
		482.6	70	X			
		551.6	80	X			
99	210	0	0	X	X	X	X
		137.9	20	X	X	X	X
		275.8	40	X	X	X	X
		344.7	50			X	X
		413.7	60	X	X	X	X
		482.6	70			X	X
		517.1	75				X
		551.6	80	X	X		
		620.5	90		X		
		689.5	100	X	X		
		827.4	120	X			
		965.3	140	X			
		1,103.2	160	X			
149	300	0	0	X	X	X	X
		137.9	20	X	X	X	X
		275.8	40	X	X	X	X
		413.7	60	X	X	X	X
		551.6	80	X	X	X	X
		620.5	90			X	
		689.5	100	X	X	X	X
		758.4	110				X
		827.4	120	X	X		
		965.3	140	X	X		
		1,103.2	160	X			

TABLE 3

HIGH-PRESSURE VISCOSITY DATA FOR FLUID MLO 75-122

Test Temperature		Test Pressure		Density		Bulk Modulus		Absolute Viscosity		Kinematic Viscosity	
°C	(°F)	MPa	(psi)	kg/m^3	(g/ml)	MPa	(psi)	mNs/m^2	(CPS)	$\mu m^2/s$	(CST)
37.8	100	0.000	0	831.700	0.8317	1,456.138	211,195	13.816	13.82	16.611	16.61
		137.895	20,000	888.400	0.8884	2,158.772	313,103	85.559	85.56	96.307	96.31
		275.790	40,000	924.300	0.9243	2,753.974	399,430	362.705	362.70	392.410	392.41
		344.738	50,000	938.500	0.9385	3,029.368	439,373	684.803	684.80	729.678	729.68
		413.685	60,000	951.100	0.9511	3,294.138	477,774	1,265.447	1,265.45	1,330.509	1,330.51
		482.633	70,000	962.500	0.9625	3,550.188	514,911	2,269.000	2,269.00	2,357.402	2,357.40
		551.581	80,000	973.000	0.9730	3,798.900	550,984	3,960.749	3,960.75	4,070.657	4,070.66
98.9	210	0.000	0	793.600	0.7936	1,080.585	156,726	4.653	4.65	5.864	5.86
		137.895	20,000	861.000	0.8610	1,761.643	255,505	13.974	13.97	16.229	16.23
		275.790	40,000	900.400	0.9004	2,325.577	337,296	38.031	38.03	42.238	42.24
		413.685	60,000	929.200	0.9292	2,834.638	411,130	92.451	92.45	99.496	99.50
		551.581	80,000	952.300	0.9523	3,309.537	480,008	208.764	208.76	219.220	219.22
		689.476	100,000	971.800	0.9718	3,760.323	545,389	442.724	442.72	455.571	455.57
		827.371	120,000	988.700	0.9887	4,192.815	608,116	898.275	898.27	908.541	908.54
		965.266	140,000	1,003.700	1.0037	4,610.750	668,733	1,754.729	1,754.73	1,748.260	1,748.26
		1,103.161	160,000	1,017.300	1.0173	5,016.710	727,612	3,323.170	3,323.17	3,266.657	3,266.66
148.9	300	0.000	0	762.400	0.7624	854.208	123,892	3.143	3.14	4.122	4.12
		137.895	20,000	838.600	0.8386	1,516.573	219,960	6.787	6.79	8.093	8.09
		275.790	40,000	880.500	0.8805	2,055.732	298,159	14.184	14.18	16.110	16.11
		413.685	60,000	910.700	0.9107	2,541.008	368,542	28.724	28.72	31.541	31.54
		551.581	80,000	934.600	0.9346	2,993.458	434,164	55.114	55.11	58.971	58.97
		689.476	100,000	954.700	0.9547	3,422.986	496,462	100.594	100.59	105.367	105.37
		827.371	120,000	972.100	0.9721	3,835.226	556,252	176.752	176.75	181.825	181.83
		965.266	140,000	987.500	0.9875	4,233.766	614,056	302.032	302.03	305.855	305.86
		1.103.161	160,000	1,001.500	1.0015	4,621.064	670,229	497.872	497.87	497.126	497.13

TABLE 4

HIGH-PRESSURE VISCOSITY DATA FOR FLUID MLO 76-121

Test Temperature		Test Pressure		Density		Bulk Modulus		Absolute Viscosity		Kinematic Viscosity	
°C	(°F)	MPa	(psi)	kg/m^3	(g/ml)	MPa	(psi)	mNs/m^2	(CPS)	$\mu m^2/s$	(CST)
37.8	100	0.000	0	854.400	0.8544	1,442.475	209,213	13.335	13.33	15.607	15.61
		137.895	20,000	912.300	0.9123	2,171.438	314,940	98.299	98.30	107.748	107.75
		206.843	30,000	931.900	0.9319	2,488.219	360,886	273.354	273.35	293.329	293.33
		275.790	40,000	948.200	0.9482	2,786.501	404,148	757.769	757.77	799.166	799.17
		344.738	50,000	962.400	0.9624	3,070.826	445,386	2,160.493	2,160.49	2,244.902	2,244.90
		379.212	55,000	968.900	0.9689	3,208.706	465,383	3,728.553	3,728.55	3,848.233	3,848.23
98.9	210	0.000	0	813.500	0.8135	1,018.350	147,699	6.026	6.03	7.408	7.41
		137.895	20,000	884.400	0.8844	1,720.282	249,506	22.172	22.17	25.070	25.07
		275.790	40,000	924.500	0.9245	2,297.170	333,176	78.021	78.02	84.392	84.39
		413.685	60,000	953.500	0.9535	2,817.199	408,600	271.201	271.20	284.427	284.43
		551.581	80,000	976.600	0.9766	3,302.172	478,940	969.688	969.69	992.923	992.92
		620.528	90,000	986.700	0.9867	3,534.984	512,706	1,851.528	1,851.53	1,876.485	1,876.48
		689.476	100,000	996.000	0.9960	3,762.524	545,708	3,566.635	3,566.64	3,580.959	3,580.96
148.9	300	0.000	0	780.000	0.7800	762.693	110,619	4.198	4.20	5.382	5.38
		137.895	20,000	862.600	0.8626	1,439.736	208,816	11.145	11.14	12.920	12.92
		275.790	40,000	905.800	0.9058	1,985.011	287,902	29.241	29.24	32.282	32.28
		413.685	60,000	936.500	0.9365	2,475.141	358,989	74.374	74.37	79.417	79.42
		551.581	80,000	960.700	0.9607	2,932.090	425,264	186.905	186.90	194.550	194.55
		689.476	100,000	980.900	0.9809	3,366.002	488,197	476.459	476.46	485.737	485.74
		827.371	120,000	998.400	0.9984	3,782.597	548,619	1,220.654	1,220.65	1,222.610	1,222.61
		965.266	140,000	1,013.800	1.0138	4,185.495	607,055	3,222.964	3,222.96	3,179.093	3,179.09

TABLE 5

HIGH-PRESSURE VISCOSITY DATA FOR FLUID MLO 77-39

Test Temperature		Test Pressure		Density		Bulk Modulus		Absolute Viscosity		Kinematic Viscosity	
°C	(°F)	MPa	(psi)	kg/m^3	(g/ml)	MPa	(psi)	mNs/m^2	(CPS)	$\mu m^2/s$	(CST)
37.8	100	0.000	0	1,785.300	1.7853	701.854	101,795	9.595	9.60	5.375	5.37
		68.948	10,000	1,905.400	1.9054	1,093.429	158,589	63.006	63.01	33.067	33.07
		137.895	20,000	1,977.200	1.9772	1,421.036	206,104	303.966	303.97	153.736	153.74
		206.843	30,000	2,029.800	2.0298	1,717.423	249,091	1,325.838	1,325.84	653.187	653.19
		241.317	35,000	2,051.800	2.0518	1,857.790	269,450	2,667.423	2,667.42	1,300.040	1,300.04
98.9	210	0.000	0	1,662.200	1.6622	439.086	63,684	3.266	3.27	1.965	1.96
		137.895	20,000	1,898.100	1.8981	1,109.344	160,897	33.286	33.29	17.536	17.54
		275.790	40,000	2,000.700	2.0007	1,630.029	236,416	219.280	219.28	109.601	109.60
		344.738	50,000	2,038.200	2.0382	1,868.557	271,011	526.579	526.58	258.355	258.35
		413.685	60,000	2,070.600	2.0706	2,097.533	304,221	1,232.977	1,232.98	595.468	595.47
		482.633	70,000	2,099.100	2.0991	2,318.950	336,335	2,934.874	2,934.87	1,398.158	1,398.16
148.9	300	0.000	0	1,561.500	1.5615	280.693	40,711	2.317	2.32	1.484	1.48
		137.895	20,000	1,843.100	1.8431	902.631	130,916	13.145	13.14	7.132	7.13
		275.790	40,000	1,952.300	1.9523	1,377.704	199,819	57.452	57.45	29.428	29.43
		413.685	60,000	2,025.700	2.0257	1,805.254	261,830	215.197	215.20	106.233	106.23
		551.581	80,000	2,082.200	2.0822	2,205.588	319,893	758.393	758.39	364.227	364.23
		620.528	90,000	2,106.500	2.1065	2,398.455	347,867	1,407.780	1,407.78	668.303	668.30
		689.476	100,000	2,128.800	2.1288	2,587.398	375,270	2,626.361	2,626.36	1,233.728	1,233.73

TABLE 6

HIGH-PRESSURE VISCOSITY DATA FOR FLUID MLO 77-46

Test Temperature		Test Pressure		Density		Bulk Modulus		Absolute Viscosity		Kinematic Viscosity	
°C	(°F)	MPa	(psi)	kg/m^3	(g/ml)	MPa	(psi)	mNs/m^2	(CPS)	$\mu m^2/s$	(CST)
37.8	100	0.000	0	1,833.500	1.8335	1,214.604	176,163	16.167	16.17	8.817	8.82
		68.948	10,000	1,914.600	1.9146	1,628.167	236,146	65.536	65.54	34.230	34.23
		137.895	20,000	1,970.100	1.9701	1,988.978	288,477	244.954	244.95	124.336	124.34
		206.843	30,000	2,013.000	2.0130	2,319.501	336,415	944.630	944.63	469.265	469.26
		275.790	40,000	2,048.300	2.0483	2,629.560	381,385	3,591.204	3,591.20	1,753.261	1,753.26
98.9	210	0.000	0	1,732.100	1.7321	794.032	115,165	5.116	5.12	2.954	2.95
		137.895	20,000	1,903.800	1.9038	1,528.700	221,719	30.947	30.95	16.255	16.26
		275.790	40,000	1,991.300	1.9913	2,118.523	307,266	163.228	163.23	81.970	81.97
		344.738	50,000	2,024.200	2.0242	2,389.025	346,499	372.818	372.82	184.180	184.18
		413.685	60,000	2,052.700	2.0527	2,648.528	384,136	840.844	840.84	409.628	409.63
		482.633	70,000	2,078.000	2.0780	2,899.231	420,498	1,886.650	1,886.65	907.916	907.92
		517.107	75,000	2,089.700	2.0897	3,021.779	438,272	2,820.370	2,820.37	1,349.653	1,349.65
148.9	300	0.000	0	1,649.200	1.6492	540.517	78,395	3.256	3.26	1.974	1.97
		137.895	20,000	1,856.300	1.8563	1,235.799	179,237	13.012	13.01	7.010	7.01
		275.790	40,000	1,951.300	1.9513	1,781.379	258,367	46.155	46.15	23.653	23.65
		413.685	60,000	2,016.500	2.0165	2,271.082	329,393	156.826	156.83	77.771	77.77
		551.581	80,000	2,067.100	2.0671	2,728.056	395,671	522.971	522.97	252.997	253.00
		689.476	100,000	2,109.000	2.1090	3,162.570	458,692	1,693.555	1,693.56	803.013	803.01
		758.423	110,000	2,127.500	2.1275	3,373.279	489,253	3,006.445	3,006.44	1,413.135	1,413.13

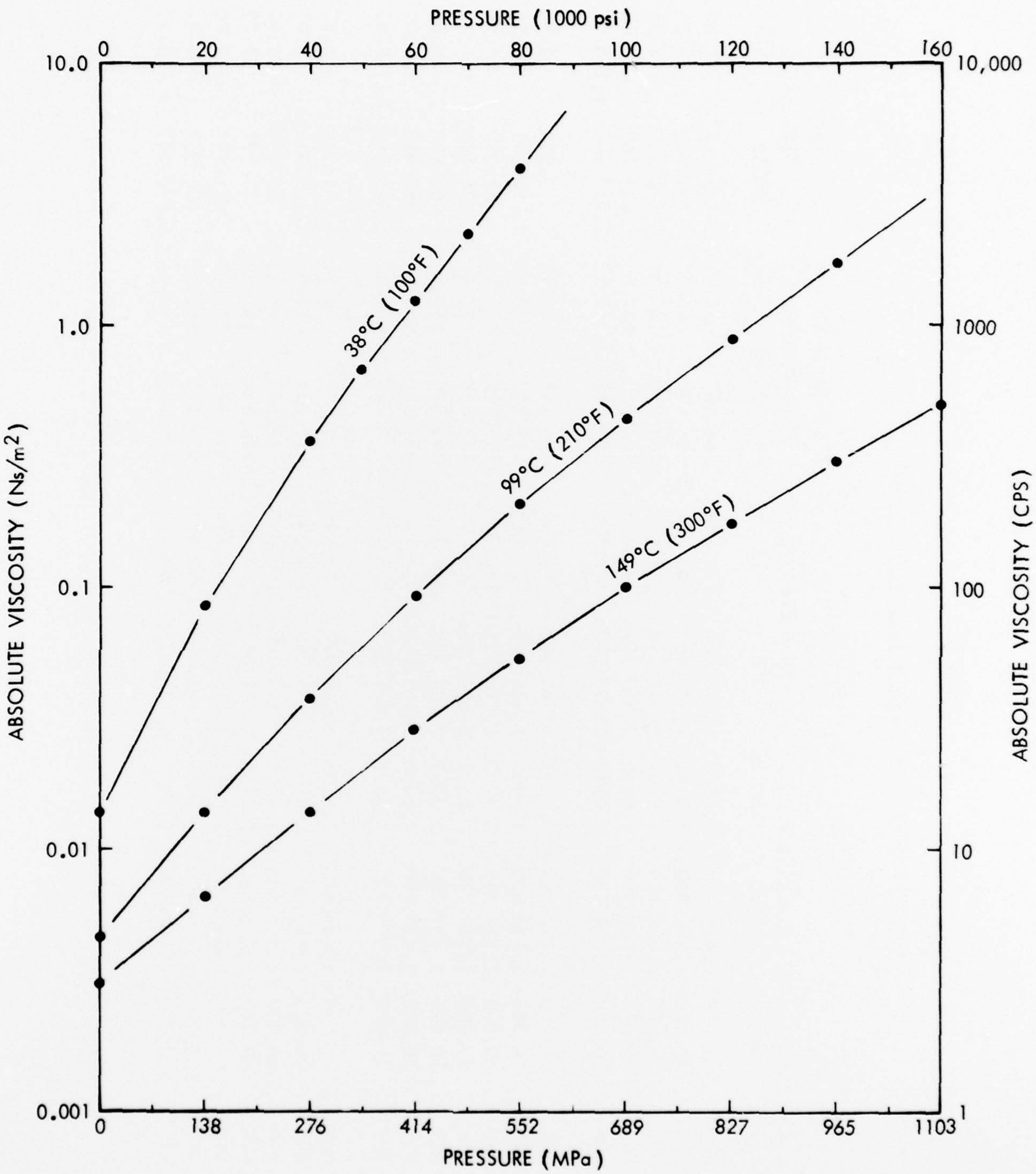


Figure 6 - Absolute Viscosity Versus Pressure - MLO 75-122

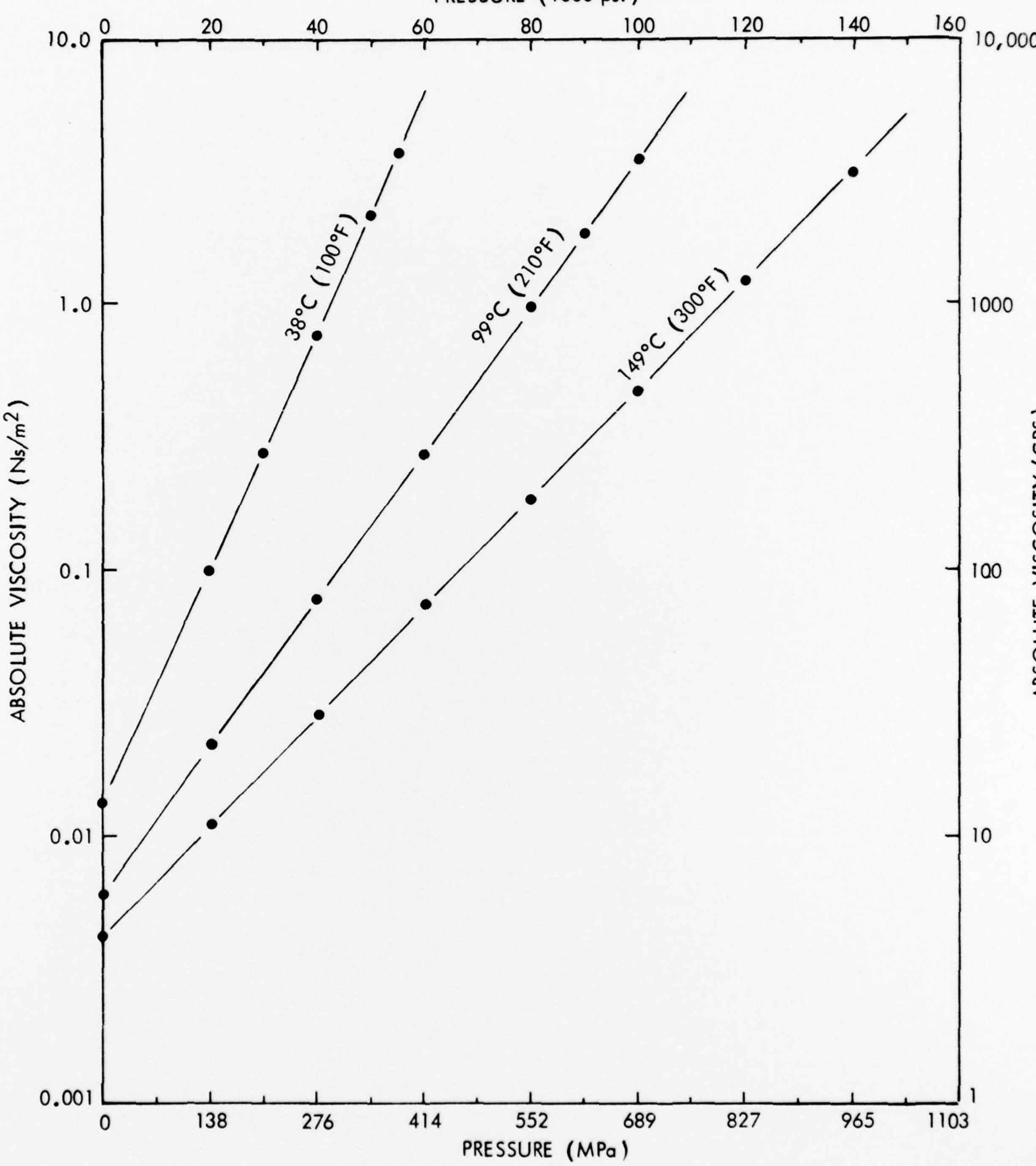


Figure 7 - Absolute Viscosity Versus Pressure - MLO 76-121

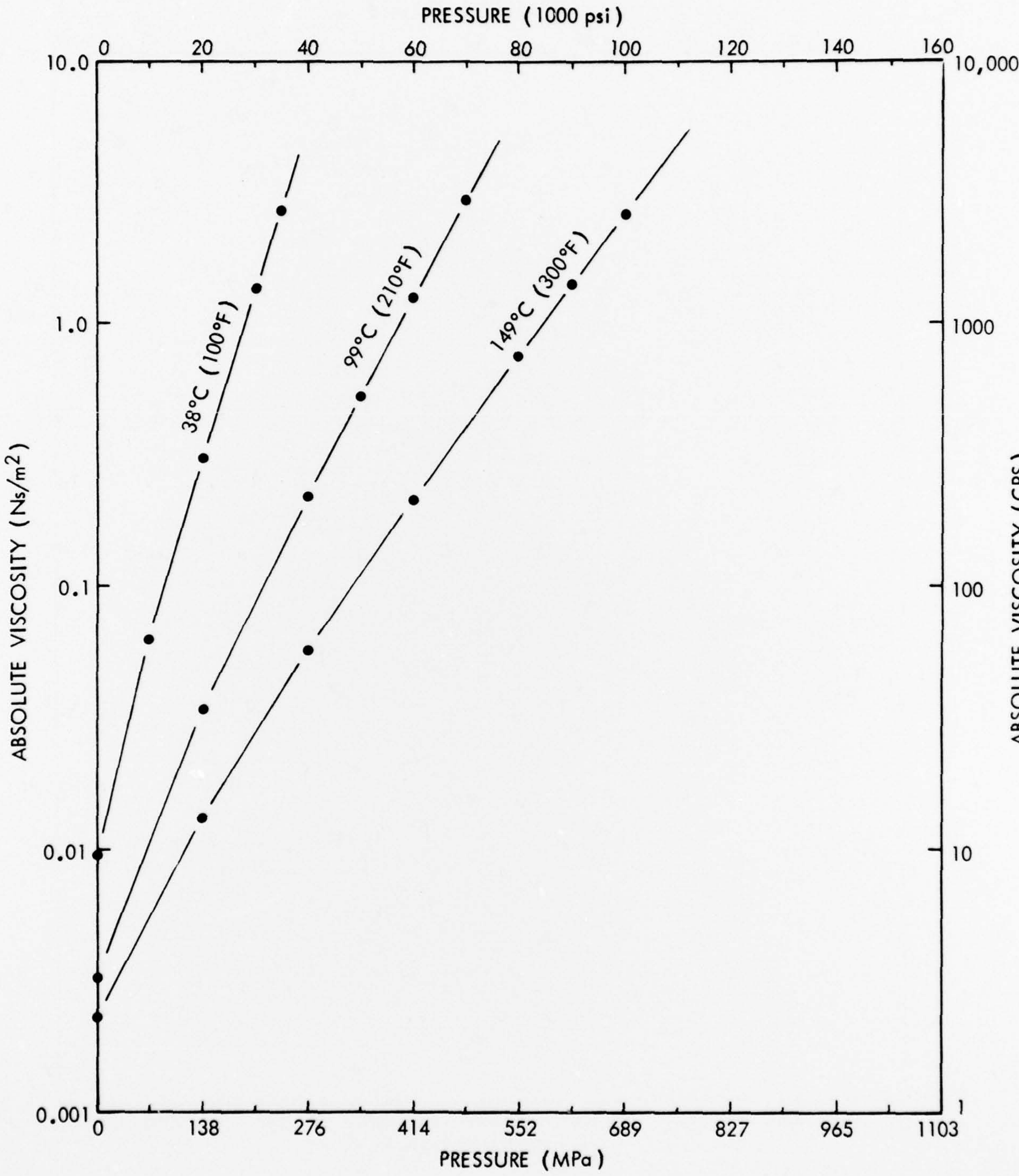


Figure 8 - Absolute Viscosity Versus Pressure - MLO 77-39

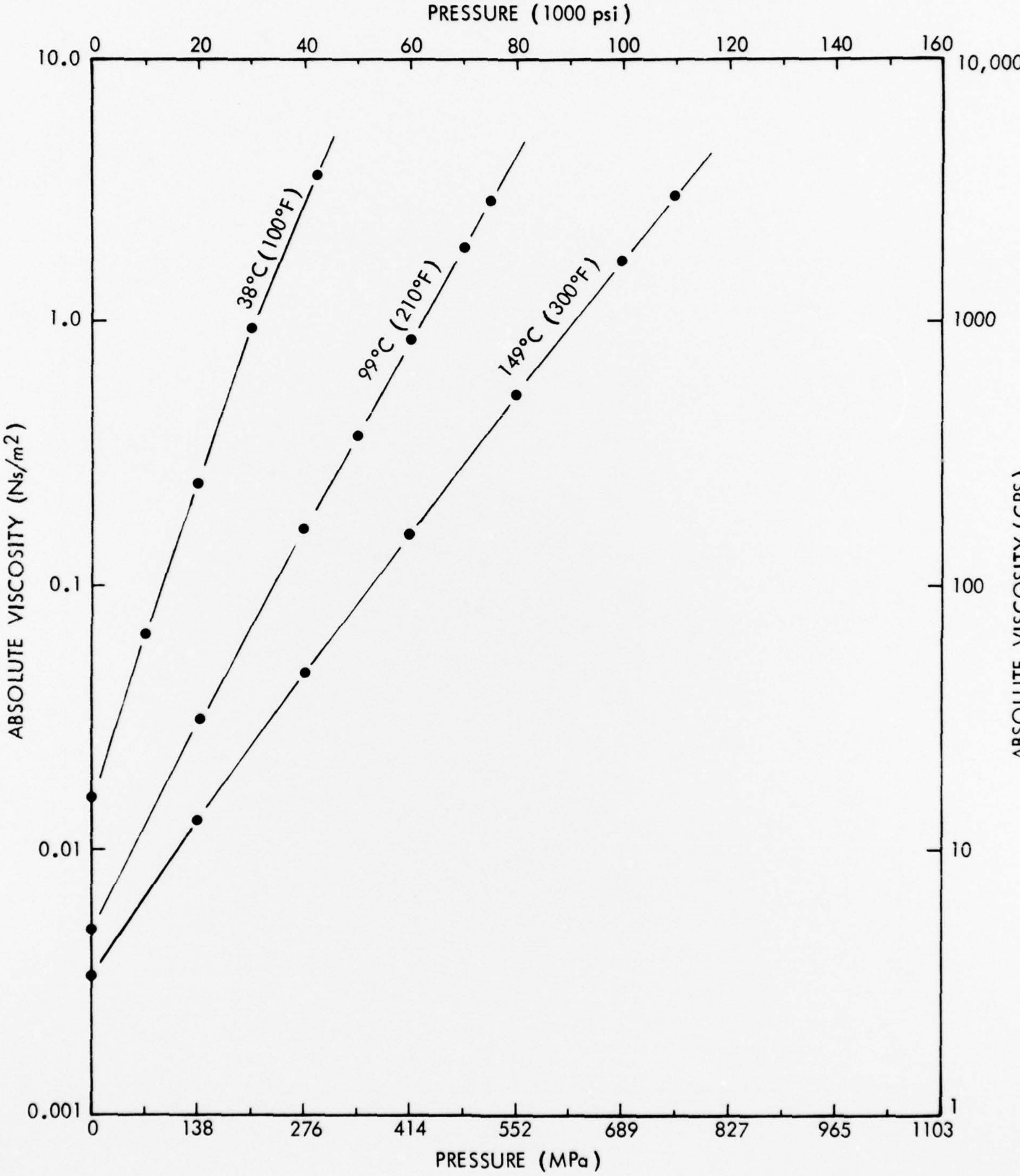


Figure 9 - Absolute Viscosity Versus Pressure - MLO 77-46

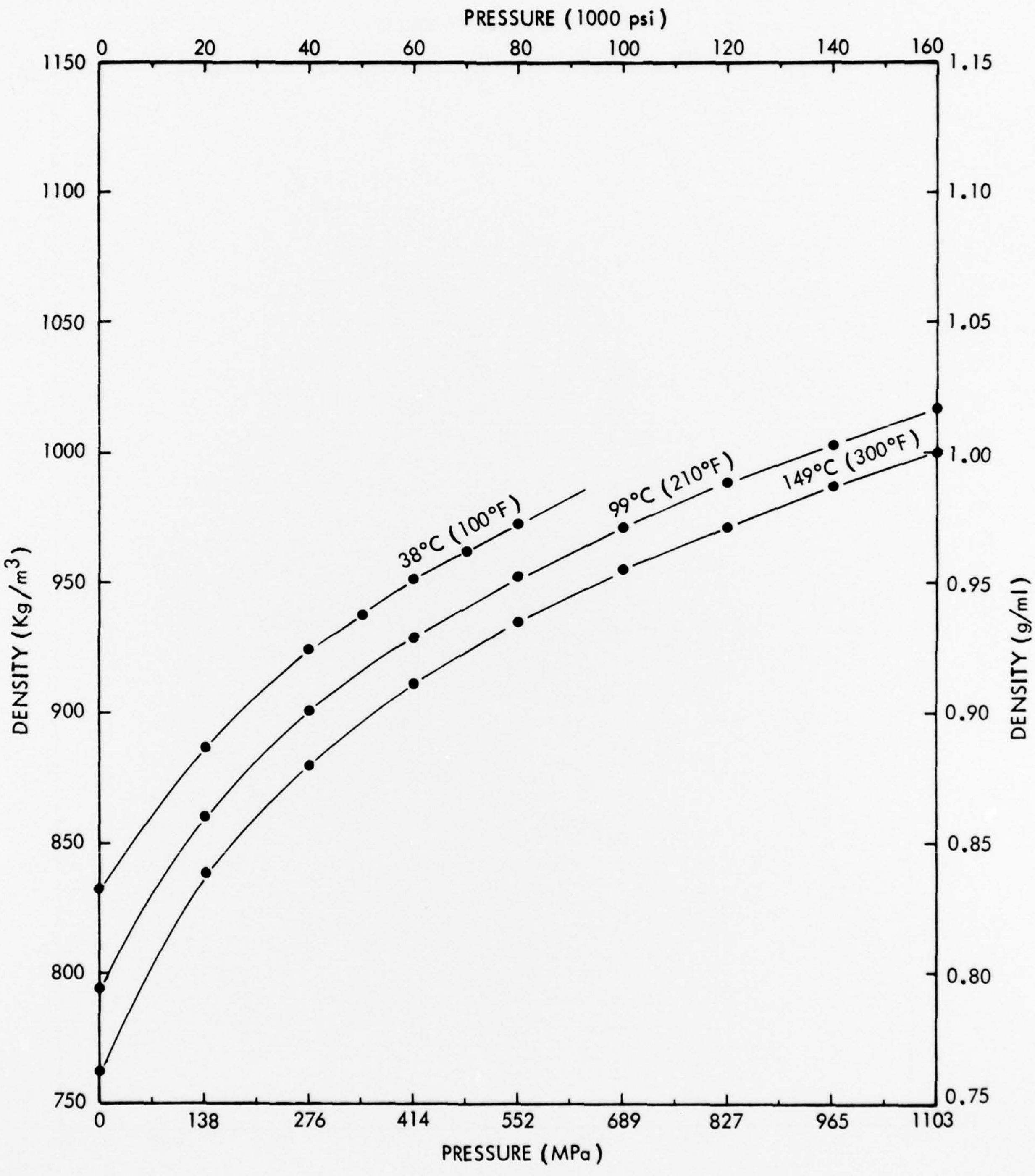


Figure 10 - Density Versus Pressure - MLO 75-122

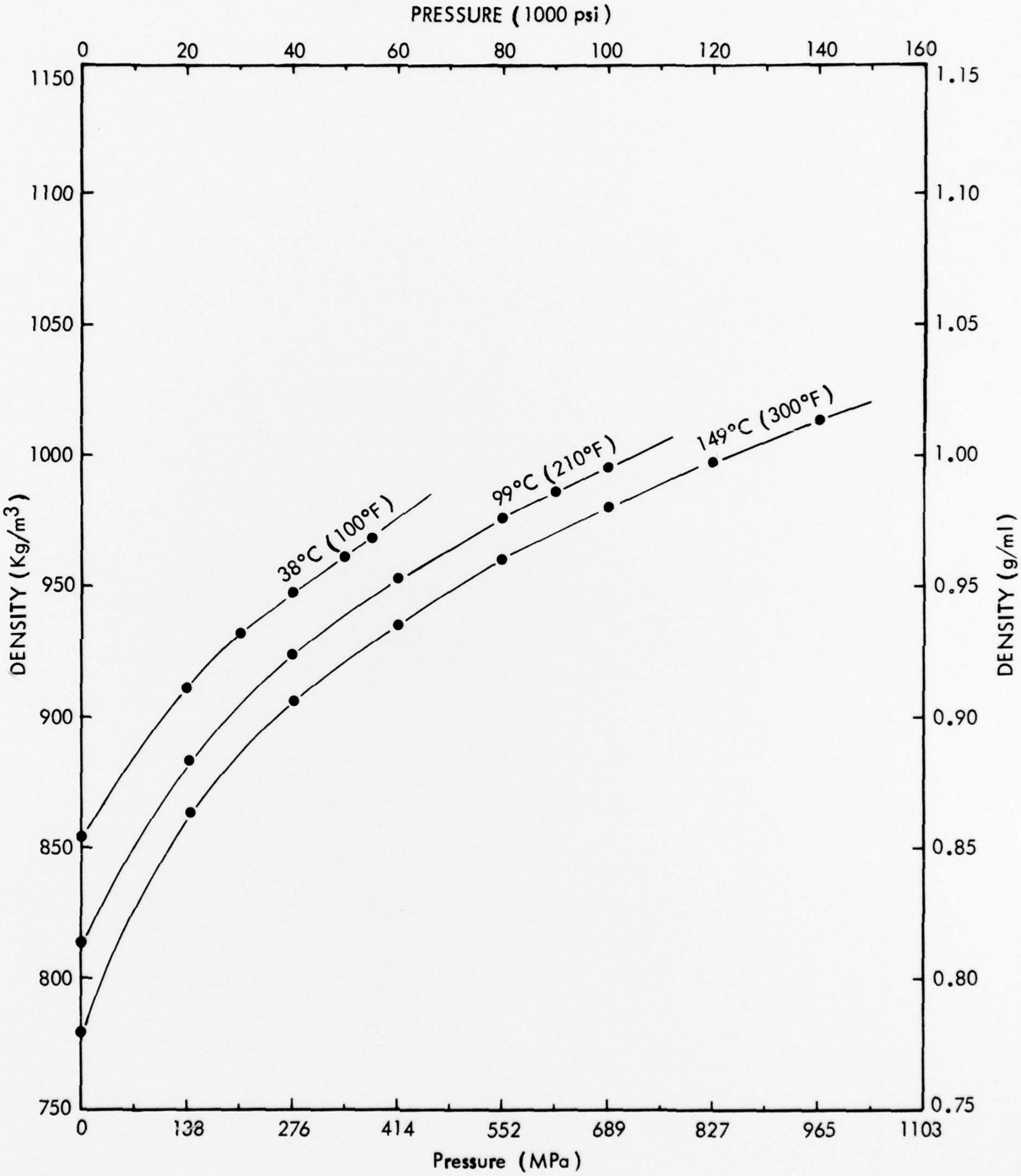


Figure 11 - Density Versus Pressure - MLO 76-121

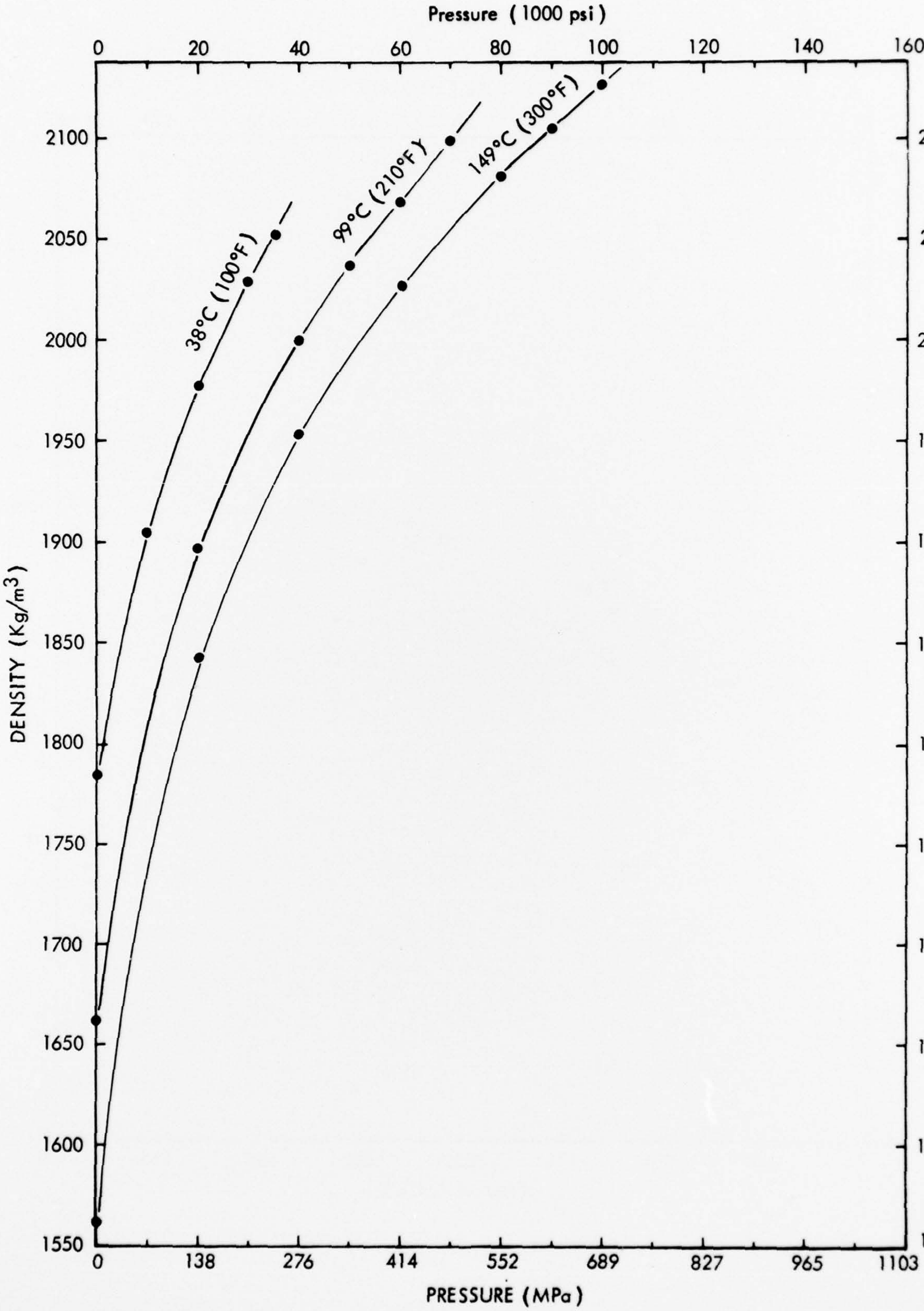


Figure 12 - Density Versus Pressure - MLO 77-39

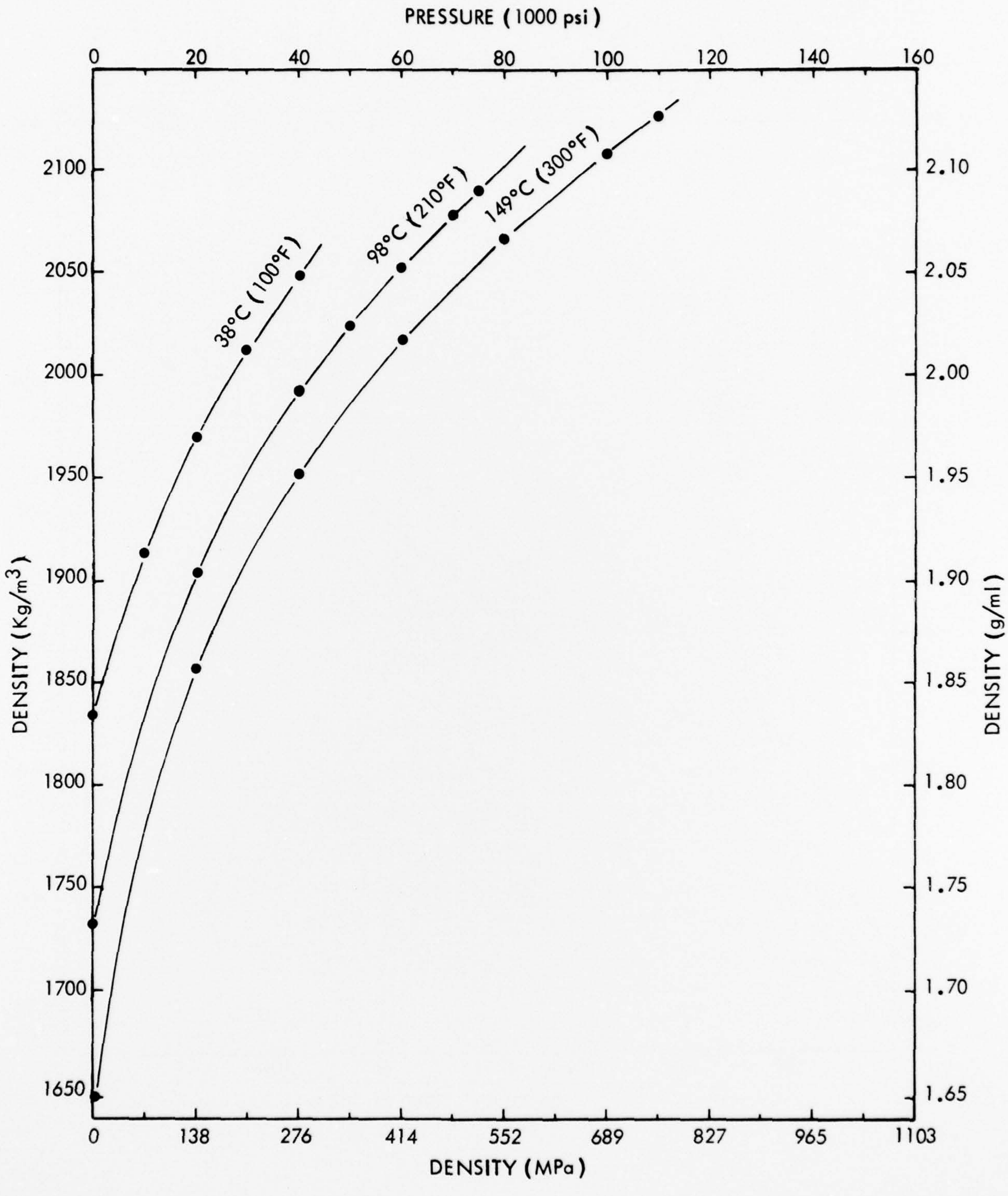


Figure 13 - Density Versus Pressure - MLO 77-46

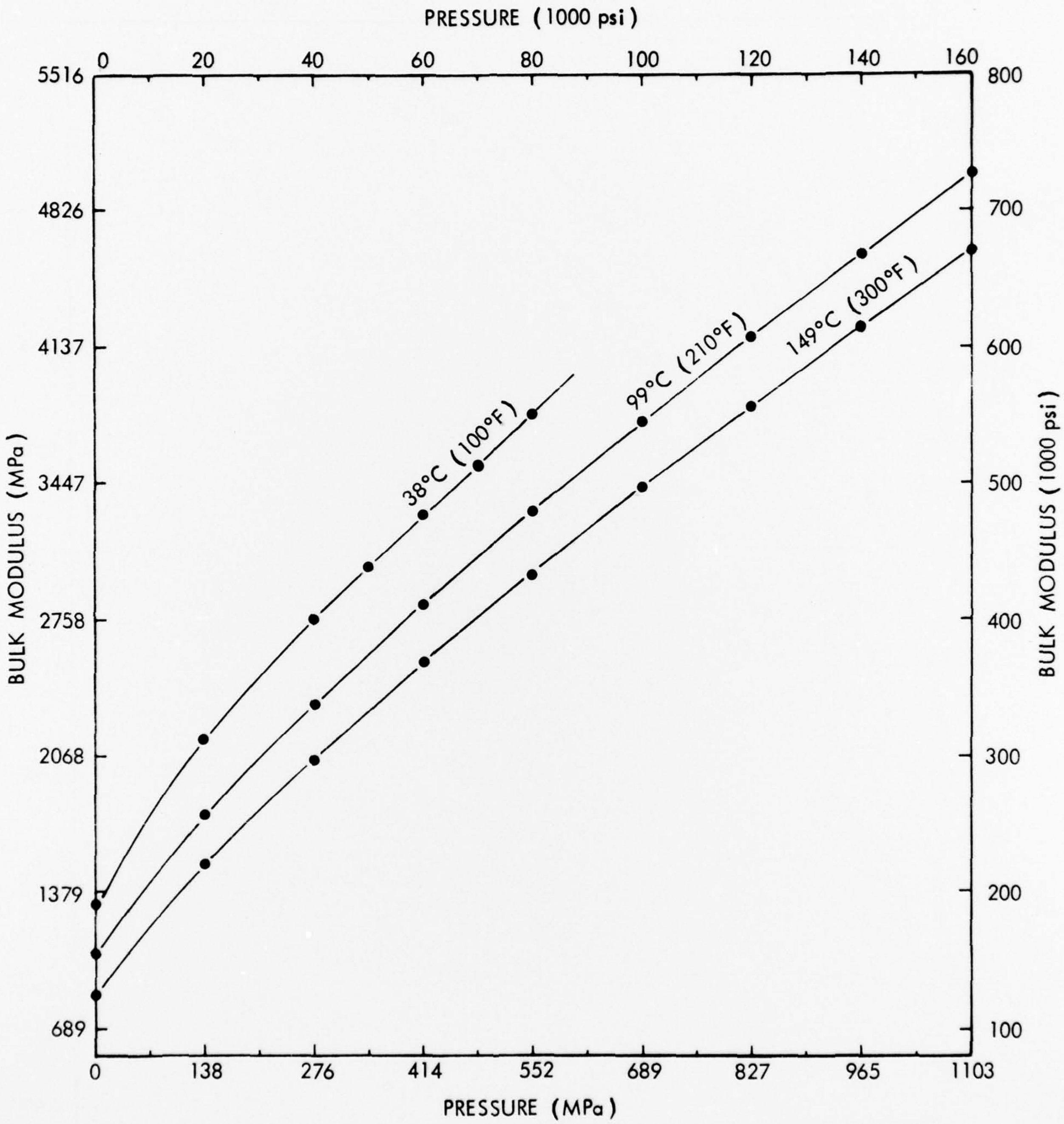


Figure 14 - Isothermal-Secant Bulk Modulus Versus Pressure - MLO 75-122

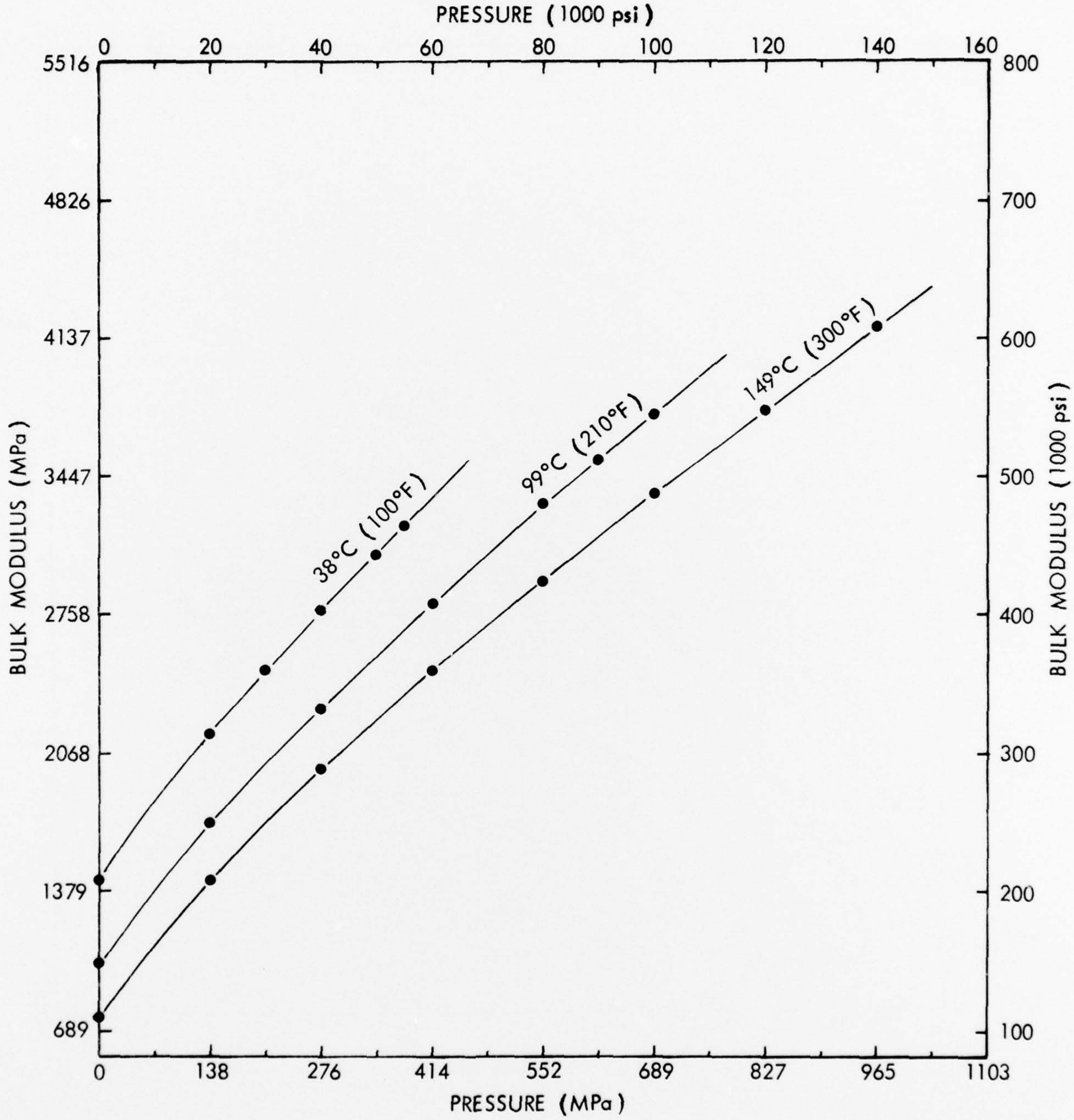


Figure 15 - Isothermal-Secant Bulk Modulus Versus Pressure - MLO 76-121

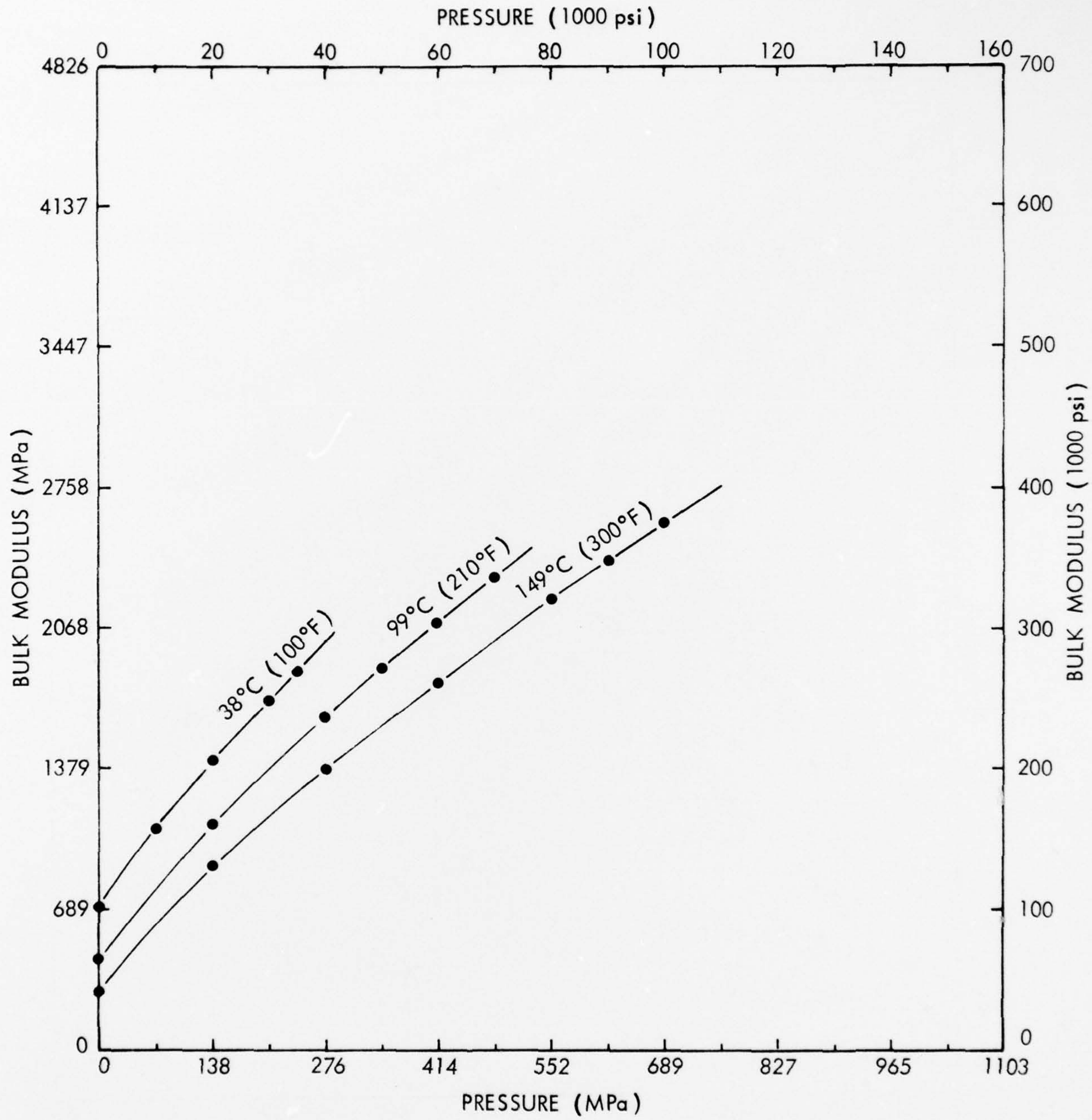


Figure 16 - Isothermal-Secant Bulk Modulus Versus Pressure - MLO 77-39

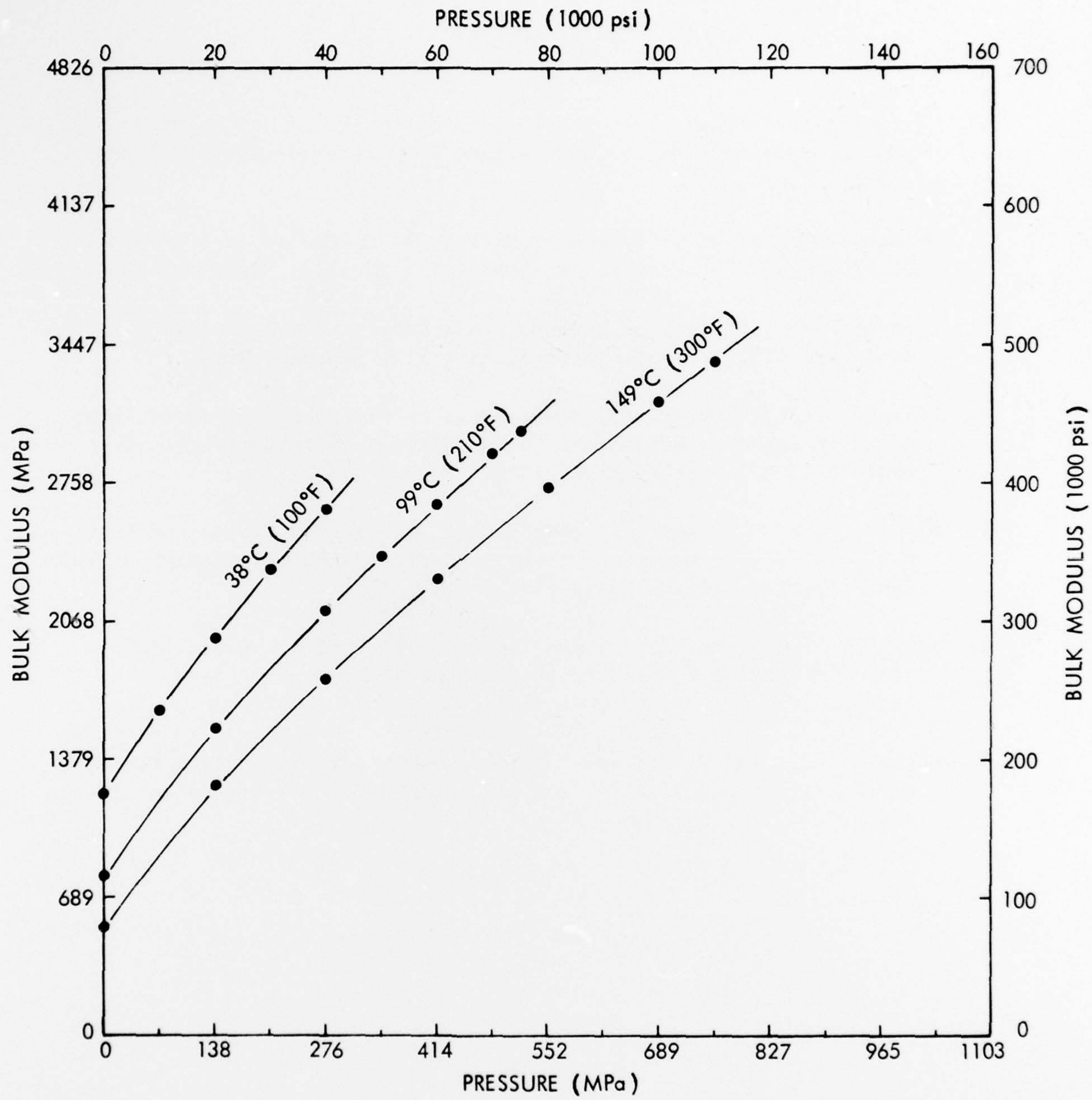


Figure 17 - Isothermal-Secant Bulk Modulus Versus Pressure - MLO 77-46

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